

# **THE GEOMORPHOLOGY OF BAA (SOUTH MAALHOSMADULU) ATOLL AND ITS REEF ISLANDS**

BY

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## **ABSTRACT**

Historically there have been few detailed geomorphic studies of the reefs and reef islands of the Maldives archipelago. The earliest studies were largely descriptive and latter studies sparse and ad hoc. Over the past decade there has been a focussed research effort in Baa Atoll (also known as South Maalhosmadulu Atoll) aimed at improving understanding of the geomorphic characteristics, morphodynamics, evolution and process controls on island formation and change. This paper synthesises this research and considers the broader significance for islands in the Maldives.

## **INTRODUCTION**

Until recently there have been few detailed studies of the geomorphology of reefs and reef islands in the Maldives archipelago. Earliest scientific investigations of the Maldives involved hydrographic observations of the archipelago by Commander James Moresby 1835–1838. This work produced detailed hydrographic charts of the reef system, which remain the most accurate records of bathymetry in the archipelago. The turn of the twentieth century saw the first expeditions to the Maldives to document the taxonomy and biogeography of reef biota and make observations of oceanographic conditions. Most notable were the expeditions of James Stanley Gardiner (1899–1900) who undertook the first descriptions of marine and terrestrial fauna and flora as well as observations of reef structure (Gardiner, 1903) and Alexander Agassiz (in 1901–1902) who undertook sampling and description of biological aspects of the reefs (Agassiz, 1903). Of note, Gardiner also made observations of some islands and reefal deposits including a selection from the reefs of southern Baa Atoll.

Between 1933 and 1934 Seymour Sewell led the “John Murray” expedition to the Maldives in which he undertook detailed geomorphic observations of a number of atolls and islands (Sewell, 1936a, b). The “Xarifa” expedition (1957-1958) undertook investigations of the sub-littoral ecology and structure of reefs in many atolls in the archipelago (Hass, 1965). This expedition was notable for its taxonomic investigation of faunal and floral communities, identification of high species diversity, and establishment of baseline monitoring locations for future reference of reef community dynamics (Wallace and Zahir, 2007). A British expedition also studied the marine and terrestrial geomorphology and ecology of Addu Atoll (Stoddart, 1966).

Based on these early observations Gardiner and Sewell speculated as to the origin, formation and process controls on island distribution (Gardiner, 1903; Sewell, 1936b). For example, cemented rocks in the island of Maamaduvvari (Baa Atoll) were interpreted by Gardiner as evidence of a higher sea level. Furthermore, Sewell (1936b) undertook detailed observations of islands in Goidhoo Atoll and surmised that island distribution was related to exposure to the oceanic swell regime with islands absent along high energy windward margins of atolls.

Since these early expeditions the research effort in the Maldives has been limited and narrowly focused on specific aspects of reef ecology, geology, and management. As a result, large gaps exist in scientific knowledge and many atolls have not been visited by scientists since Gardiner and Sewell. However, over the past decade there has been a concerted effort to investigate aspects of reef and island geomorphology in Baa Atoll. This paper summarises this work and examines the geomorphological characteristics of Baa Atoll and its reef islands. The focus of the paper is on the Holocene development of the atoll and its islands based on a synthesis of recent field investigations. Results are discussed in light of future trajectories of reef islands in Baa Atoll.

## **GEOLOGICAL SETTING**

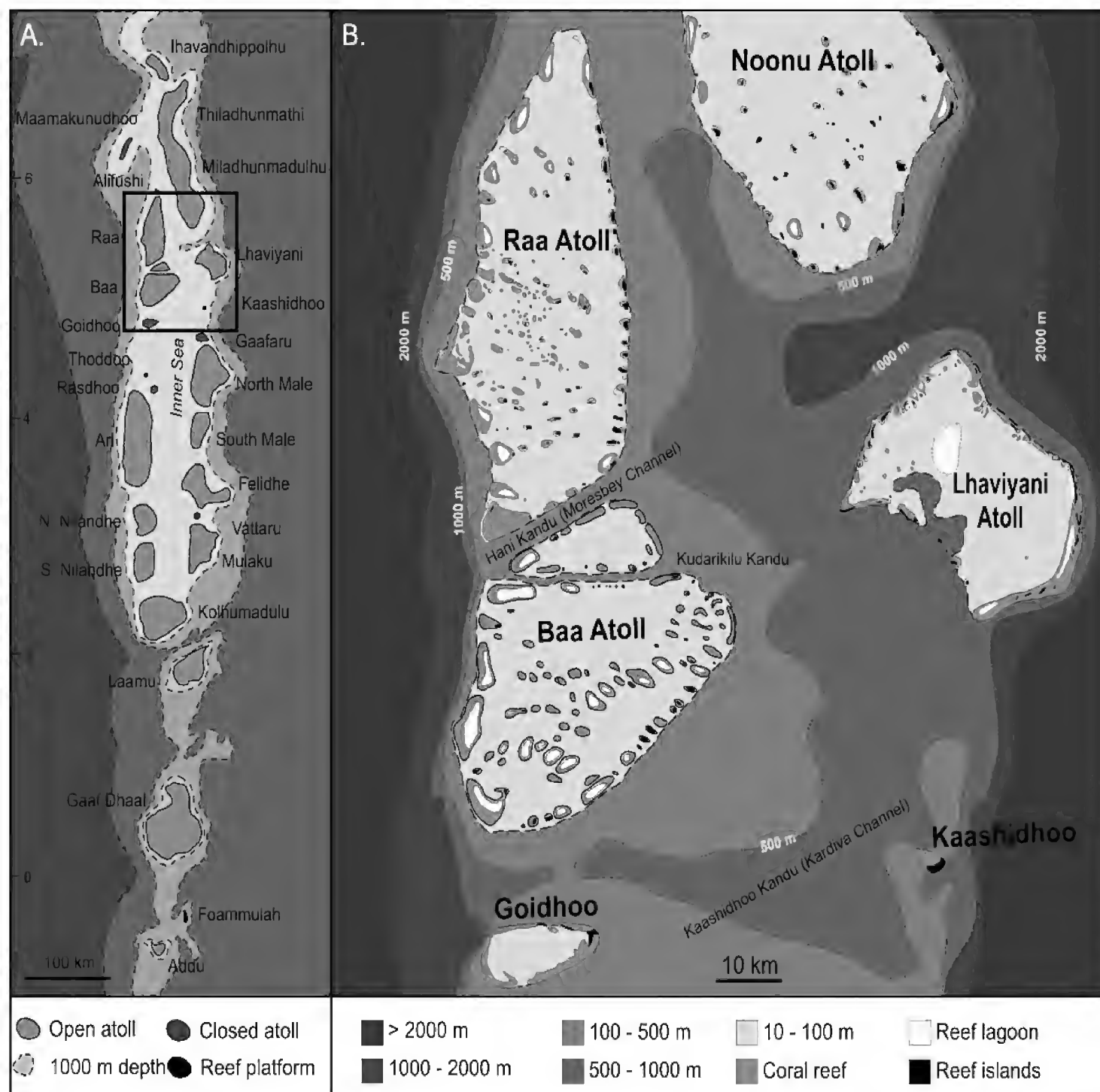
The Maldives archipelago comprises a chain of coral reefs and reef islands situated 700 km southwest of Sri Lanka (Fig. 1). The archipelago extends 868 km from Ihavandhippolhu in the north (6°57' N) to Addu Atoll (0°34' S) just south of the equator. Comprising 2,041 reefs (Naseer and Hatcher, 2004) the archipelago is globally unique in biological diversity, the range reef structures it possesses and their mode of evolution.

The archipelago constitutes the central section of the Laccadives – Maldives – Chagos submarine ridge, which in turn is part of a larger feature that stretches from the early Tertiary Deccan Traps of India to the volcanically active zone of Reunion. The Deccan Traps were the first manifestation of the stationary mantle hotspot that subsequently produced the volcanic ridge underlying the Maldives. Northward drift of the Indian Plate and northeastward motion of the African plate has resulted in northward age progression along this ridge (Duncan and Pyle, 1988; Duncan and Hargreaves 1990; Tiwari et al., 2007).

The history of formation of the Maldivian atoll systems differs to the subsidence model proposed by Darwin (1842). The basement rocks underlying the Maldives are Eocene volcanics (55 million years old). These basement volcanics are capped by up to 3,000 m of limestones. Carbonate accumulation through the Tertiary was controlled by phases of aggradation and progradation modulated by large oscillations in sea level (Aubert and Droxler, 1992; Purdy and Bertram, 1993; Belopolsky and Droxler, 2003; Kench, 2011). During the Quaternary the dominant mode of reef development has been vertical coral reef growth. This vertical reef growth is a consequence of high-amplitude sea-level fluctuations during the Pliocene-Pleistocene, producing alternate periods of exposure and submergence. During periods of submergence reefs accreted vertically to fill the accommodation space. The Holocene is the most recent of these reef growth phases.

## Climatic Controls

The physical characteristics of atolls and reefs of the Maldives show marked latitudinal variations. Northern atolls are characterized by a heavily dissected atoll reef rim, numerous lagoonal patch reefs and faros and moderate lagoon depths (40-50 m).



**Figure 1.** Field setting of the Maldives archipelago and Baa atoll (A). Regional setting of Baa and neighbouring atolls (B).

Reef islands are located on the peripheral and lagoonal patch reefs of these northern atolls. In contrast, southern atolls are characterized by more continuous atoll reef rims, higher proportion of peripheral reef rim containing islands, few lagoonal patch reefs and deeper lagoons (70-80 m, Woodroffe, 1993).

Longitudinal variations in morphology have been attributed to broad north-south gradients in climate and oceanographic conditions. The archipelago is subject to monsoonal conditions that switch from the west to northeast in a predictable fashion. The intensity of oscillating monsoon conditions increases to the north. Incident wave energy and rainfall both reduce in magnitude and intensity toward the north. Spatial gradients in

boundary controls can influence rates of solutional lowering of lagoons during glacial and sediment transport and island formation processes on reef platforms. periods, and during highstands can control contemporary coral reef growth, sediment production

## PHYSIOGRAPHIC CHARACTERISTICS OF BAA ATOLL

Baa Atoll is located in the Northern Province and western side of the double chain of atolls that comprise the Maldives archipelago (Fig. 1). Baa is surrounded by a number of other atolls: Raa Atoll to the north, separated by the narrow Moresby Channel; Noonu and Lhaviyani Atolls to the northeast and east, on the eastern side of the inner sea; and, the enclosed Goidhoo Atoll located approximately 20 km to the south (Fig. 1B). Collectively these neighbouring atolls afford a measure of protection to oceanic swell energy impacting Baa Atoll from the north to eastern sectors. To the southeast and also located on the eastern margin of the inner sea is the small reef platform island Kaashidhoo. However, the small size of this platform and distance from Baa suggest its influence on energy exposure is limited. Baa is exposed to ocean swell along its western and southwest margins.

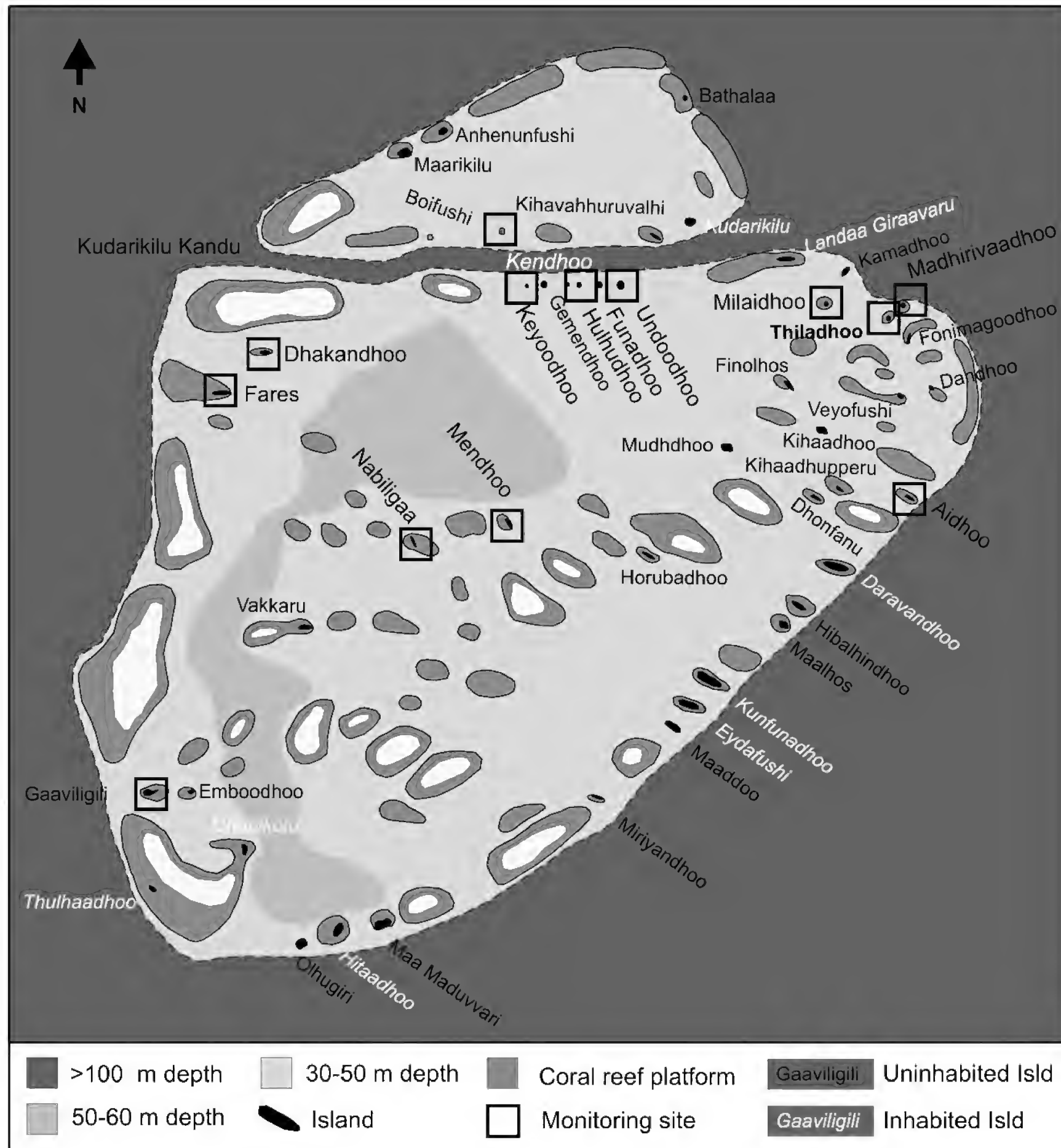
The western reefs of Baa Atoll grade steeply to depths in excess of 1000 m. In contrast, on the eastern boundary the bathymetry of the shallow inner sea grades more gently to 500 m (Fig. 1B). Channels separating Baa Atoll from Raa in the north and Goidhoo in the south reach depths of 240 m and 560 m respectively.

At the gross scale the structure of Baa Atoll can be divided into two sections; a large triangular-shaped rim of reef platforms in the south and a smaller triangular rim of reefs in the north separated by the narrow Kudarikilu Kandu (channel; Fig. 2). A network of individual reef platforms that extend 122 km and enclose a lagoon of 1,127 km<sup>2</sup> defines the atoll periphery. The atoll is 38 km wide (on its longest west-east axis) and 46 km long along the southwest to northeast axis.

Baa Atoll contains 105 individual reef platforms with a total reef area of 263 km<sup>2</sup>. The size and location of the reef platforms varies markedly within the atoll. Forty-nine reefs occur on the atoll margin. The western rim of Baa comprises six large platforms that have a maximum length of 8.2 km and 4.2 km width. Most of these western reefs have internal lagoons. The remainder of the atoll periphery is characterised by smaller reef platforms typically less than 1 km in maximum length and 0.5 km in width (Fig. 2). There are 56 lagoon reefs, most of which are clustered in the southern and central sector of the lagoon. A number of lagoonal reefs also straddle either side of the Kudarikilu Channel in the north. Eleven of the lagoon reefs are faro.

There are a total of 33 major passages that connect the open ocean and lagoon around atoll rim. These passages range in width up to 4.2 km with a total passage length of 44.5 km. Consequently, the atoll structure can be categorised as 'open', with an effective aperture of 0.37. The bathymetry of Baa Atoll is characterised by passages that in general are 35-56 m in depth. One exception is the narrow Kudarikilu channel where depths reach 256 m. The depth of the majority of the lagoon ranges from 30-50 m. However, there is a slightly deeper sector that ranges from 50 m to 60 m located in southwestern and central section of the lagoon (Fig. 2).

There are 61 vegetated islands and at least four unvegetated sand cays located on the reef platforms of Baa Atoll. The spatial distribution, geomorphological and sedimentological characteristics of these islands are described in detail in this study.



**Figure 2.** Baa Atoll detailing the distribution of reefs and reef islands.

### Oceanographic Regime

The climate of the Maldives can be divided into two monsoon periods marked by strong reversals in wind direction that are confined to a narrow range of wind angles. Summary wind data since 1964 (Fig. 3A, B) indicate that the Maldives experience

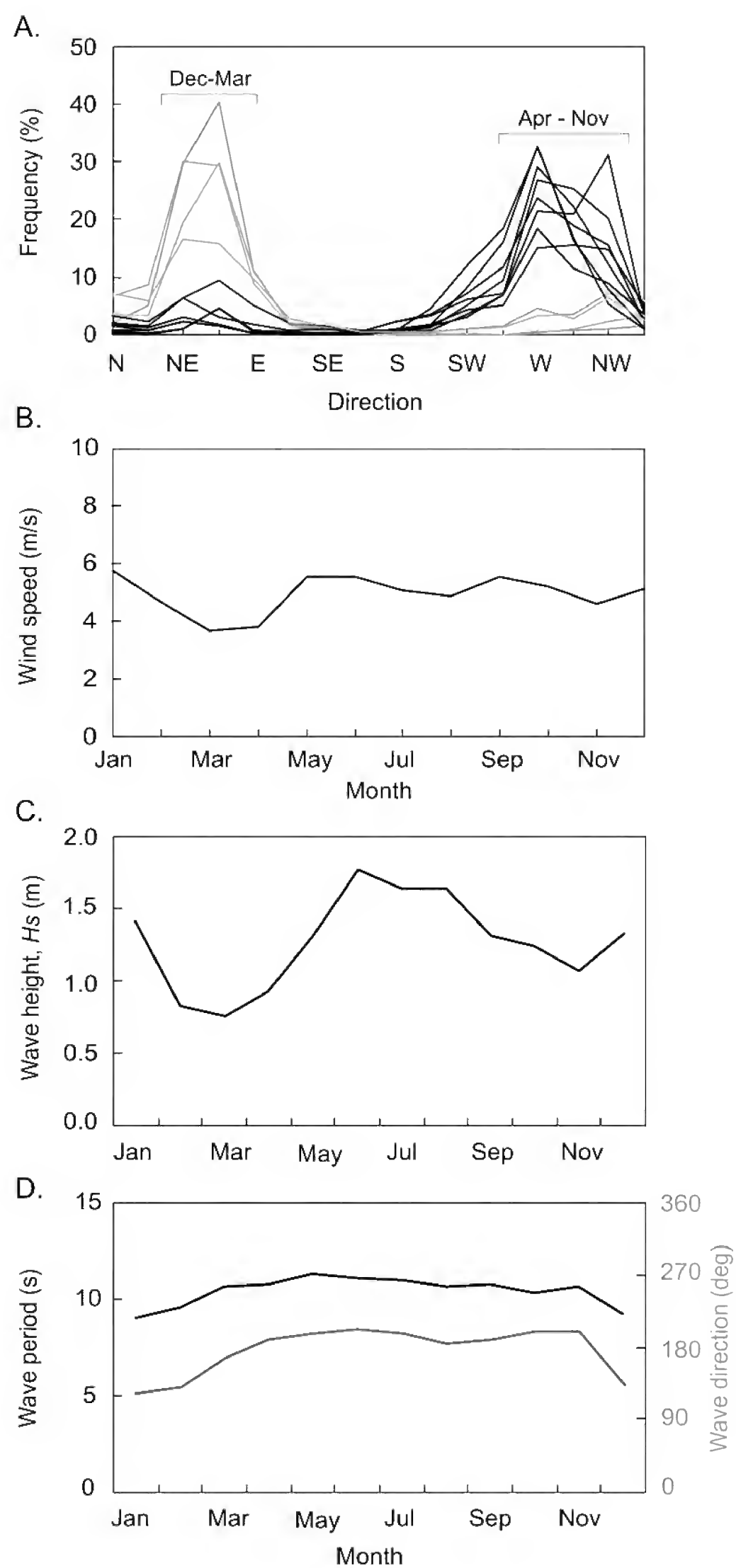


southwest to northwest winds ( $\sim 225\text{--}315^\circ$ ) from April to November (westerly monsoon) with a mean wind speed of  $5.0\text{ ms}^{-1}$ . In contrast, winds from the northeast-east ( $\sim 45\text{--}90^\circ$ ) prevail from November to March (northeast monsoon) with a mean wind speed of  $4.8\text{ ms}^{-1}$  (Fig. 3A, B). Wind strength is most variable during the cross-over between northeast and westerly monsoons with mean wind speed falling to  $3.5\text{ ms}^{-1}$  in March (Department of Meteorology, 1995).

Information on the deepwater wave climate is limited, but satellite altimetry wave climate data (for a ten-year period) for the region (Young 1999) indicates the dominant swell approaches from southerly directions (Fig. 3D). On a seasonal basis, swell is from the south-southwest from April to November with a peak significant wave height ( $H_s$ ) of 1.8 m in June, and from the south to southeast directions from November to March with a minimum  $H_s$  of 0.75 m in March (Fig. 3C, D).

The broadscale oceanography of the atolls of the Maldives has been poorly studied. Atoll-specific circulation and current patterns are controlled by the interaction of tide and wave processes with atoll structure. As noted above, the heavily dissected character of the Baa Atoll rim indicates the effective aperture of the atoll (proportion of gaps in the reef) is 37%. Consequently, the atoll is considered to be ‘open’ and allows penetration of tides and waves into the lagoon. The atoll is influenced by a microtidal regime with a spring tide range of approximately 1.2 m.

At the atoll scale Kench et al. (2006) examined wave processes across Baa Atoll. They showed that wave energy affecting the atoll varies between monsoon seasons and is spatially variable within the atoll in each monsoon. Wave energy impacting the atoll is considerably greater during the westerly monsoon. Furthermore, atoll structure promotes significant changes in wave energy and wave characteristics across the atoll. Short period (3-8 s) monsoon-driven wave energy, which is significant on windward reefs, is dissipated on the peripheral reef network and the density of lagoonal patch reefs limits development of locally generated wind wave energy across the lagoon. However, longer period swell (8-20 s) propagates through the lagoon to leeward reefs. A windward to leeward decay in wave energy was evident in the westerly monsoon, but not in the northeast monsoon, when long period swell (from the southwest) remains significant on western reefs. Net energy calculations that account for seasonal changes in wave energy across the atoll identify a steep west-east gradient. In general, western reefs are dominated by westerly flowing energy that is 4.5-7 times the total energy input elsewhere in the atoll. Wave energy on central reefs is balanced whereas net energy on eastern reef platforms is dominated by eastward propagating energy. This steep energy gradient is likely to have geomorphic significance for reef growth and reef island development change throughout the atoll. As shown by Kench et al. (2006), for each individual reef platform incident wave energy is controlled by the relative presence or absence of boundary oceanic swell, the monsoonally forced wind-waves generated external and internal to the lagoon, as well as local sheltering factors promoted by proximity to other reefs.



**Figure 3.** Summary of Maldives wind and wave climate over a 10 year period. A) Percent frequency monthly wind direction. B) Mean wind speed. C) Significant wave height in region of Baa Atoll. D) Wave period and direction in region of Baa Atoll.

## HOLOCENE REEF DEVELOPMENT

The contemporary surface morphology of the Maldivian reefs is the result of coral reef growth on Pleistocene foundations over the past 10,000 years. The Holocene reef growth history of the Maldives has only recently been resolved in detail based on drill cores from Ari and Baa Atolls (Gischler, 2008; Kench et al., 2009a). Of relevance to this discussion are three closely spaced rotary drill cores extracted from the Hulhudhoo reef flat in the central section of Baa Atoll lagoon. A summary of the drill cores from Hulhudhoo is presented in Figure 4 and radiometric dates on 23 coral samples from the cores are summarised in Table 1. The data provide insights into the Holocene development of reefs in Baa Atoll.

### Reef Cores

The outer reef flat core penetrated 14.6 m through the outer reef surface and terminated in highly porous reef rock with recrystallisation and discoloration, characteristic of Last Interglacial reef limestone (Montaggioni, 2005; Woodroffe, 2005). Overlying this basal rock the core comprised alternating massive corals (predominantly poritids and faviids) and coral rubble (with encrusting coralline algae and little sand matrix).

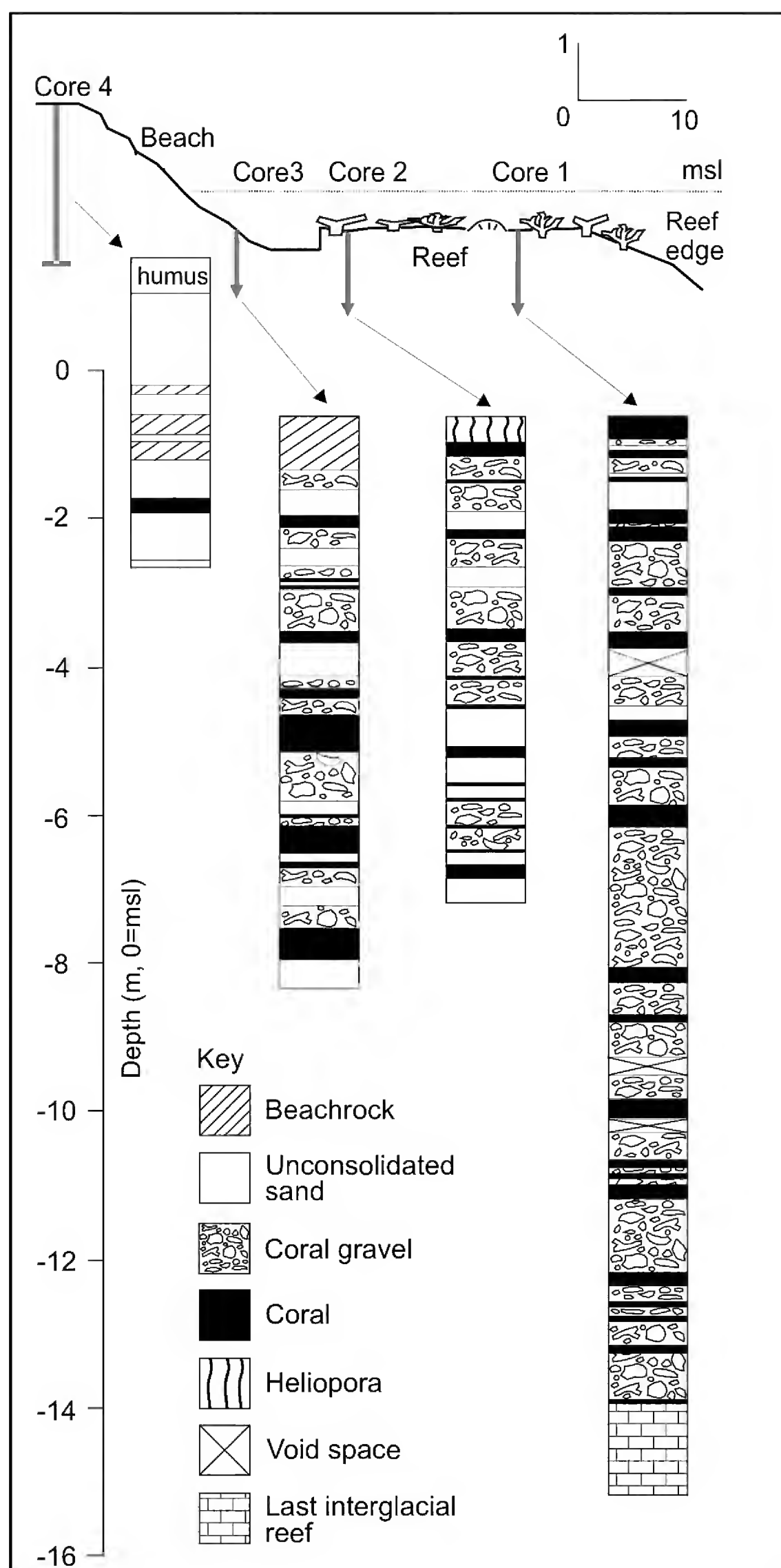
The central and inner reef flat cores penetrated 6.2 m and 7.2 m below the reef surface respectively, terminating in *Halimeda*-rich sand (Fig. 4). Above these basal sediments the cores comprised alternating layers of massive corals (*poritids*, *acroporids* and *faviids*), coral rubble and sand (Fig. 4A). A fourth core was extracted through the island ridge using a combination of hand auger and drill techniques (Kench et al., 2005). The island ridge core penetrated unconsolidated, medium-grained island sands in the upper 1.6 m before encountering multiple layers of cemented sand (beach rock or cay sandstone). Underlying the island sediments in situ coral and reefal sediments were encountered.

Kench et al. (2009a) noted a number of conspicuous features of the massive corals in cores. First, favid and acroporid species dominate below a depth of 5 m. Second, poritid corals dominate the core above 5 m as well as on the contemporary reef flat. Third, the growth structure and orientation of corallites within the massive corals are indicative of in situ growth position and the thickness of the fossil corals in cores (typically 0.2 to 0.4 m) was comparable to that of living microatolls on reef flats surrounding the study islands.

### Radiometric Ages of Core Material and Reef Growth

Uranium-series dating of the basal reef sample in core 1 yielded a minimum age of  $122,000 \pm 7.0$  ka (at -14.12 below msl) confirming this limestone as Last Interglacial reef. Results of dating coral material above the interglacial surface provide the timing of reef establishment and chronology of reef growth in the Holocene. An age of ca 8,100 cal yBP (Table 1), immediately overlying the Last Interglacial surface records the initiation of the Holocene reef growth on Hulhudhoo. This age for Holocene reef initiation is comparable to that from Rasdhoo Atoll (Gischler et al., 2008) and other oceanic reefs in the western Indian Ocean (Montaggioni, 2005). Further dates indicate steady vertical reef growth followed from ca 8,100 to 6,400 cal yBP (to a water depth of -2.17 m below msl)





**Figure 4.** Reef drill cores on southern Hulhudhoo reef flat, Baa Atoll, Maldives. Topography of island margin and reef flat shown at top. After Kench et al., 2009a.

Table 1. Radiometric ages from reef cores and microatolls on Hulhudhoo and Funadhoo Islands, Baa atoll.

| Lab code | Island and sample location | Sample material        | Depth relative to MSL(m) | Conventional age (yr B.P.) | Calibrated age range (95.4% probability)(cal. yr B.P.) |
|----------|----------------------------|------------------------|--------------------------|----------------------------|--|
| 20801    | HUL C1                     | <i>Favid sp.</i>       | -13.89                   | 7,802 ± 53                 | 8,302 - 7,970  |
| 20802    | HUL C1                     | <i>Favid sp.</i>       | -13.17                   | 7,758 ± 51                 | 8,258 - 7,935  |
| 20803    | HUL C1                     | <i>Favid sp.</i>       | -12.17                   | 7,732 ± 50                 | 8,227 - 7,914  |
| 20804    | HUL C1                     | <i>Favid sp.</i>       | -11.07                   | 7,465 ± 50                 | 7,940 - 7,646  |
| 20805    | HUL C1                     | <i>Favid sp.</i>       | -8.07                    | 7,053 ± 48                 | 7,558 - 7,290  |
| 20806    | HUL C1                     | <i>Favid sp.</i>       | -6.07                    | 6,864 ± 48                 | 7,413 - 7,119  |
| 20807    | HUL C1                     | <i>Favid sp.</i>       | -5.27                    | 6,846 ± 48                 | 7,404 - 7,083  |
| 20808    | HUL C1                     | <i>Porites sp.</i>     | -4.77                    | 6,566 ± 47                 | 7,128 - 6,742  |
| 20809    | HUL C1                     | <i>Favid sp.</i>       | -3.72                    | 6,292 ± 46                 | 6,759 - 6,419  |
| 20810    | HUL C1                     | <i>Porites sp.</i>     | -2.17                    | 6,144 ± 46                 | 6,599 - 6,280  |
| 20811    | HUL C1                     | <i>Porites sp.</i>     | -1.17                    | 4,872 ± 46                 | 5,226 - 4,826  |
| 20812    | HUL C1                     | <i>Porites sp.</i>     | -0.87                    | 4,548 ± 52                 | 4,798 - 4,401  |
| 20818    | HUL C2                     | <i>Acropora sp.</i>    | -6.87                    | 6,882 ± 47                 | 7,415 - 7,145  |
| 20819    | HUL C2                     | <i>Acropora sp.</i>    | -6.17                    | 6,840 ± 57                 | 7,406 - 7,056  |
| 20820    | HUL C2                     | <i>Pocillopora sp.</i> | -5.12                    | 6,551 ± 47                 | 7,113 - 6,723  |
| 20821    | HUL C2                     | <i>Porites sp.</i>     | -4.17                    | 6,614 ± 61                 | 7,177 - 6,768  |
| 11302    | HUL C2                     | <i>Porites sp.</i>     | -2.50                    | 5,802 ± 60                 | 6,210 - 5,910  |
| 20813    | HUL C3                     | <i>Favid sp.</i>       | -7.87                    | 7,078 ± 48                 | 7,571 - 7,310  |
| 20814    | HUL C3                     | <i>Favid sp.</i>       | -6.72                    | 7,052 ± 48                 | 7,557 - 7,290  |
| 20815    | HUL C3                     | <i>Porites sp.</i>     | -5.17                    | 6,769 ± 57                 | 7,322 - 6,954  |
| 20816    | HUL C3                     | <i>Porites sp.</i>     | -2.87                    | 6,041 ± 46                 | 6,474 - 6,182  |
| 20817    | HUL C3                     | <i>Porites sp.</i>     | -1.36                    | 4,404 ± 42                 | 4,567 - 4,168  |
| 11302    | HUL C4                     | Reef rock              | -1.17                    | 4,078 ± 70                 | 4,140 - 3,720  |
| 12663    | HUL RF                     | <i>Porites</i> FMA     | -0.25                    | 3,679 ± 45                 | 3,550 - 3,340  |
| 20797    | FUN RF                     | <i>Porites</i> FMA     | -0.06                    | 2,566 ± 39                 | 2,278 - 1,911  |
| 20798    | FUN RF                     | <i>Porites</i> FMA     | -0.06                    | 2,578 ± 45                 | 2,289 - 1,919  |

*Note:* Radiocarbon dates obtained from the Radiocarbon Dating Laboratory, University of Waikato, New Zealand. Ages calibrated by using OxCal version 3.5 (Bronk Ramsey, 2001) with the marine data set (Stuiver et al., 1998) and Delta-R value of  $132 \pm 25$  as best estimate for the central Indian Ocean reservoir effect (Southon et al., 2002). FMA = fossil microatoll, HUL = Hulhudhoo, FUN = Funadhoo. From Kench et al. 2009a.

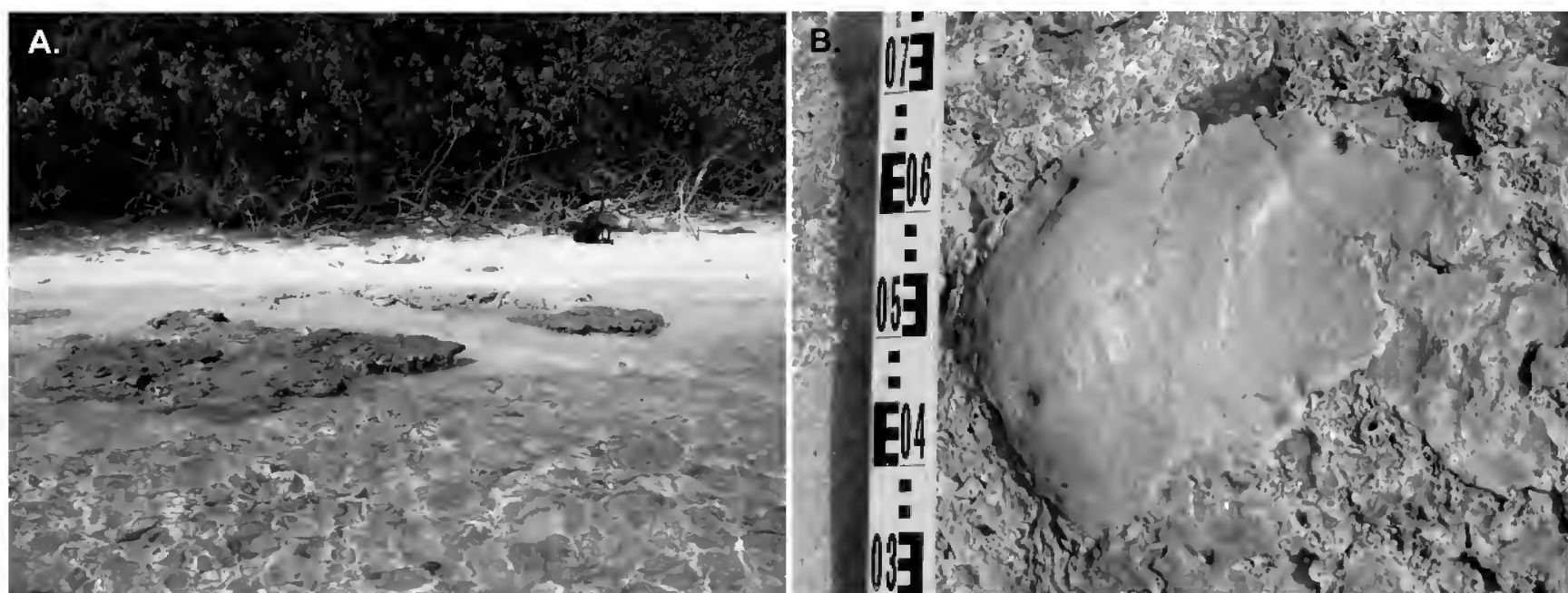
at a mean rate of  $\sim 7$  mm/y. The rate of vertical reef accretion then slowed to  $\sim 0.8$  mm/y ca 6,400 cal yBP, the reef first reaching near its present level approximately 4,000-4,500 yr ago. Ages of the uppermost poritids from cores 1 and 2 and of *in situ* fossil *Heliopora* in core 4 have an age range from ca 3,900 to 4,600 cal yBP suggesting the Hulhudhoo reef reached its maximum width at this time.

Comparison of the age and elevation of dated corals between cores indicates that: reef development was dominated by vertical growth from ca 8,000 to 6,500 cal yBP with no evidence of lateral extension of the fore reef to seaward. Subsequently, the outer section of reef accreted at a faster rate than the inner reef between ca 6,500 and 4,500 yr ago (Table 1).

## Emergent Reef Flat Corals

In addition to reef cores a number of radiometric dates were obtained from emergent fossil microatolls on Hulhudhoo and the neighbouring island Funadhoo (Fig. 2, 5). On Hulhudhoo, a sample from one *Porites* microatoll dated at ca 3,400 cal yBP is situated  $0.25 \pm 0.07$  m below msl, which is  $0.18 \pm 0.05$  m above the upper limit of present living microatolls. Samples from two *Porites* microatolls dated at ca 2,100 cal yBP from Funadhoo were up to  $0.37 \pm 0.06$  m above the upper limit of contemporary coral growth ( $0.06 \text{ m} \pm 0.06 \text{ m}$  below msl; Table 1). These microatolls outcrop at the island shoreline and overlie *in situ* fossil *Heliopora* (Fig. 5).

Seasonal movements of beach sands and coral rubble have abraded the upper surfaces of these fossil microatolls (Fig. 5). Thus the surveyed elevations represent minimum palaeo-sea level positions. Observations of the mean thickness of living microatolls throughout the atoll suggest that as much as 0.15-0.2 m has been removed by abrasion. It is conservatively estimated that coral growth occurred to at least  $0.5 \pm 0.1$  m above present around 2,100 yBP. The presence of emergent fossil microatolls has profound implications for understanding sea level change.

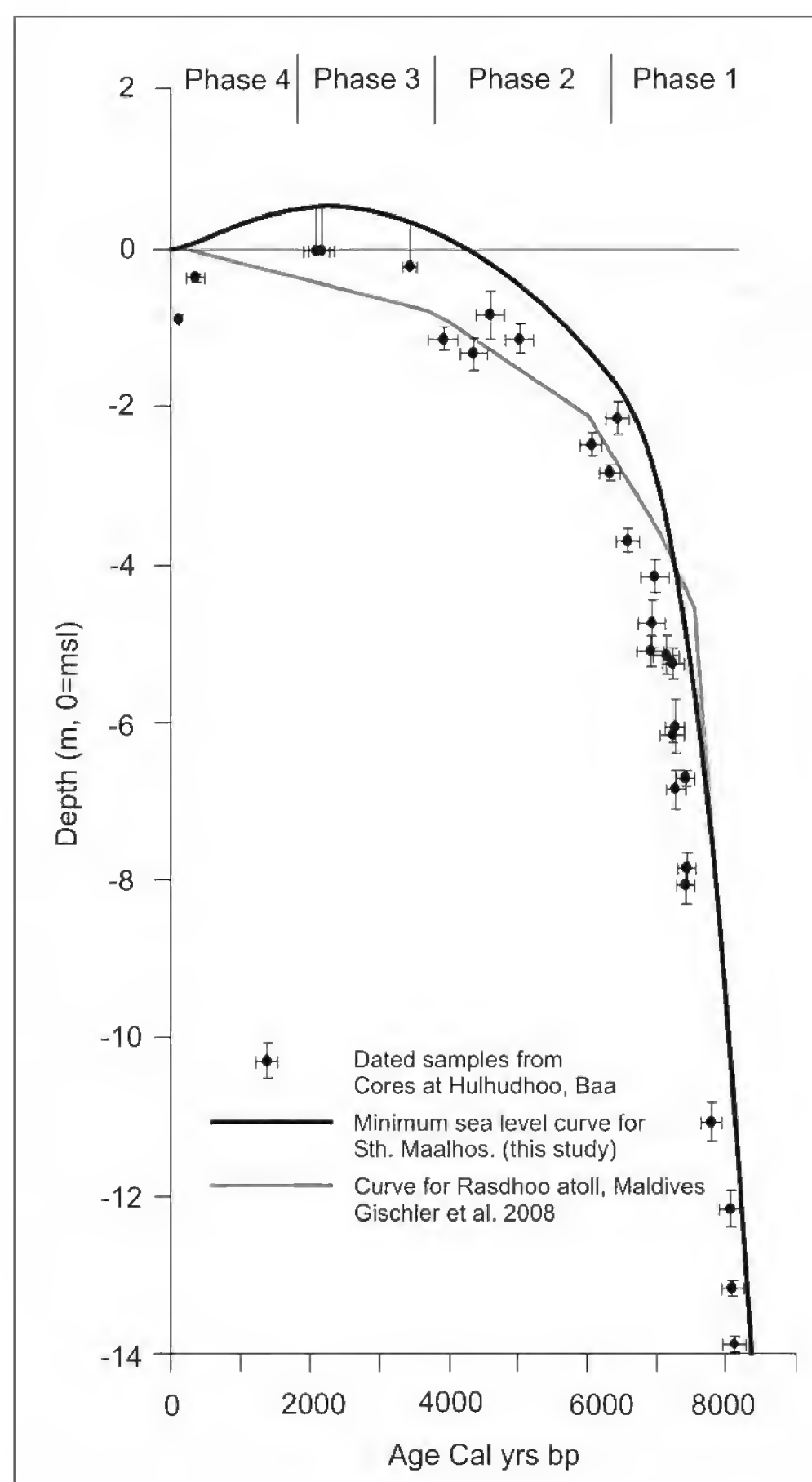


**Figure 5.** Photograph of *Heliopora* reef capped by fossil microatolls outcropping on eastern shoreline of Funadhoo (A). Photograph taken two hours prior to high tide. B) Abraded fossil microatoll in growth position above fossil *Heliopora* surface.

## Sea Level History

The presence of massive living poritid and faviid corals, including microatolls, on the contemporary reef flats of Baa Atoll, together with the frequent occurrence of their fossil equivalents throughout the Hulhudhoo cores is indicative of a comparable palaeo-reef setting, suggesting that accretion of the Hulhudhoo reef closely tracked rising sea level. The presence of emergent fossil *in situ* microatolls provides a higher resolution late-Holocene sea-level indicator as their upper growth surface is constrained by subaerial exposure during low tides (Smithers and Woodroffe, 2000).

Based on these interpretations the Holocene sea level history in Baa Atoll can be inferred. The sea level record is divided into four distinct phases (Fig. 6). Phase 1 is characterised by a steady sea-level rise of  $\sim 7$  mm/y, which flooded the last interglacial



**Figure 6.** Age-depth plot of reef core and fossil microatoll samples. Inferred minimum sea level history represented by black line. Horizontal bars represent  $2\sigma$  calibrated age range (Table 1) and vertical bars are defined by uncertainties of coral elevation. After Kench et al., 2009a.

surface around 8,100 to 6,500 cal yBP. Phase 2 spanned the period 6,500 to 4,500 cal yBP and is characterised by decrease in the rate of sea-level rise to  $<1$  mm/y. Sea level first reached present level at around 4,500 cal yBP. During Phase 3 sea level continued to rise to at least  $0.5 \pm 0.1$  m above present until ca 2,100 cal yBP. The fourth and final phase is the subsequent falling of sea level from the late-Holocene highstand to its current elevation.

These results clarify the pattern of Holocene sea level change in Baa Atoll which is of relevance to the entire Maldives archipelago. Of note, the mid-Holocene reef growth

history is comparable to that described by Gischler et al. (2008) on Rasdhoo Atoll, although no evidence for a higher sea level was found at that location. The elevated microatolls on Baa provide unequivocal evidence of a late-Holocene sea level highstand ca 2,000-4,000 yr ago. At a regional scale these results are significant as they confirm that emergent reef build-ups are not missing from the central Indian Ocean as suggested by Camoin et al. (2004).

## **REEF ISLANDS OF BAA ATOLL**

Baa Atoll contains 61 vegetated reef islands which are located on peripheral and lagoonal reef surfaces. In addition there are at least four unvegetated and ephemeral unvegetated sand cays. The vegetated islands and unvegetated sand cays in Baa are diverse in their morphological and sedimentary characteristics. As identified earlier physical descriptions of some of the islands in the southern part of the atoll were undertaken by Gardiner (1903) and provide a basis to examine island change.

Over the past decade there has been an increased research effort to better understand the geomorphic characteristics of islands in Baa Atoll, their evolution and morphodynamics (Ali, 2000; Kench and Brander, 2006; Kench et al., 2005; Kench et al., 2006; 2008). In particular, 13 islands throughout Baa Atoll were identified and established as the first sites of geomorphic monitoring in the Maldives (Fig. 2). These islands have been the focus of repetitive geomorphic surveys and mapping since 2002. Monitoring observations have been used to examine seasonal variations in island shorelines (Kench and Brander, 2006) and assess the impacts of the Indian Ocean tsunami on islands (Kench et al. 2006, 2007, 2008; Nichol and Kench 2008).

### **Physical Characteristics of Islands**

The islands of Baa Atoll are found both on the peripheral reef rim (n=34) and internal lagoon reefs (n=31). A number of observations can be made with regard to the physical distribution of islands. First, there are only three islands located on the western exposed rim of the atoll and these are all small in size. Second, the highest density of islands occurs on the southern to eastern peripheral rim of the atoll. Third, exploration of descriptive characteristics between lagoonal and peripheral islands identified few meaningful differences. However, average island area is greater on peripheral islands (10.9 ha) compared to lagoonal islands (7.6 ha; Table 2).

Physical dimensions of islands are summarised in Table 3. Island size ranges from less than 1 hectare to more than 45 hectares. Over half of all islands (38) are less than 10 hectares in area and collectively account for 19% of total land area in the atoll. Islands between 10 and 30 hectares in area (23 in total) account for 67.5% of atoll land area. Of note, only two islands are larger than 30 hectares. Dharavandhoo is the largest island in the atoll at 45.5 ha in area. This elongate island is 1.32 km in length and 480 m in width. The second largest island Kunfunadhoo is 35 hectares in area. Collectively these two

islands account for 13% of total land area in the atoll. Islands occupy varying proportions of their reef platforms ranging from less than 1% to a maximum of 71% on Olhugiri ( $x=23\%$ ). Islands are also found in a broad spectrum of planimetric shapes from linear to near circular. In general, island shape mirrors reef platform shape except where there are multiple islands on reefs or where the island is extremely small compared with reef area.

Table 2. Summary of vegetated island size classes in Baa atoll.

| Island size  | No. islands | Total island area<br>(hectares) | Percent of total<br>island area |
|--------------|-------------|---------------------------------|---------------------------------|
| < 1.0        | 6           | 2.1                             | 0.35                            |
| 1.0-9.99     | 30          | 110.3                           | 18.6                            |
| 10.0 – 19.99 | 15          | 211.2                           | 35.6                            |
| 20-29.99     | 8           | 189.3                           | 31.9                            |
| 30-39.99     | 1           | 35.0                            | 5.9                             |
| >40          | 1           | 45.5                            | 7.7                             |

### Geomorphic Characteristics of Islands

Surveys depicting the morphology of islands have been undertaken on 43 of the islands in Baa Atoll (Ali, 2000; Kench and Brander, 2006). Typical island cross-sections are presented in Figure 7 and can be divided into 3 characteristic morphologies. 1) Convex islands with simple convex ridges (Fig. 7A). Unvegetated sand cays or small vegetated islands which can experience washover under higher water level conditions typically exhibit this morphology. 2) Asymmetric islands with a high seaward ridge which slopes lagoonward. The island surface typically terminates in a more subdued ridge on the opposite side of the island (Fig. 7B). 3) Basin shape islands where high marginal ridges impound a lower elevation central depression (Fig. 7C). This is the most common island morphology and is typical of the medium to larger islands in the atoll.

There is significant variation in the elevation of island ridges. Ali (2000) reported a maximum ridge elevation on Funadhoo of 3.19 m above mean sea level (msl). Kench et al. (2008) show marked changes in ridge elevation both within islands and across the atoll that are related to energy exposure. In general, highest ridge elevations occur where shorelines are exposed to higher wave energy. Examining islands across a west to east transect Kench et al. (2008) found consistent variations in island ridge elevation within islands, with western exposed island ridges typically 0.5-1.2 m higher than leeward island ridges. Furthermore, they showed that the eastern island Thiladhoo had much lower elevation ridges (1.08 – 1.59 m) than western and central islands (1.44-2.51 m range). Kench et al. (2008) suggest the dominant westerly monsoon wave conditions are responsible for such spatial patterns with higher wave energy promoting greater swash excursion on island shorelines and greater run-up deposition.

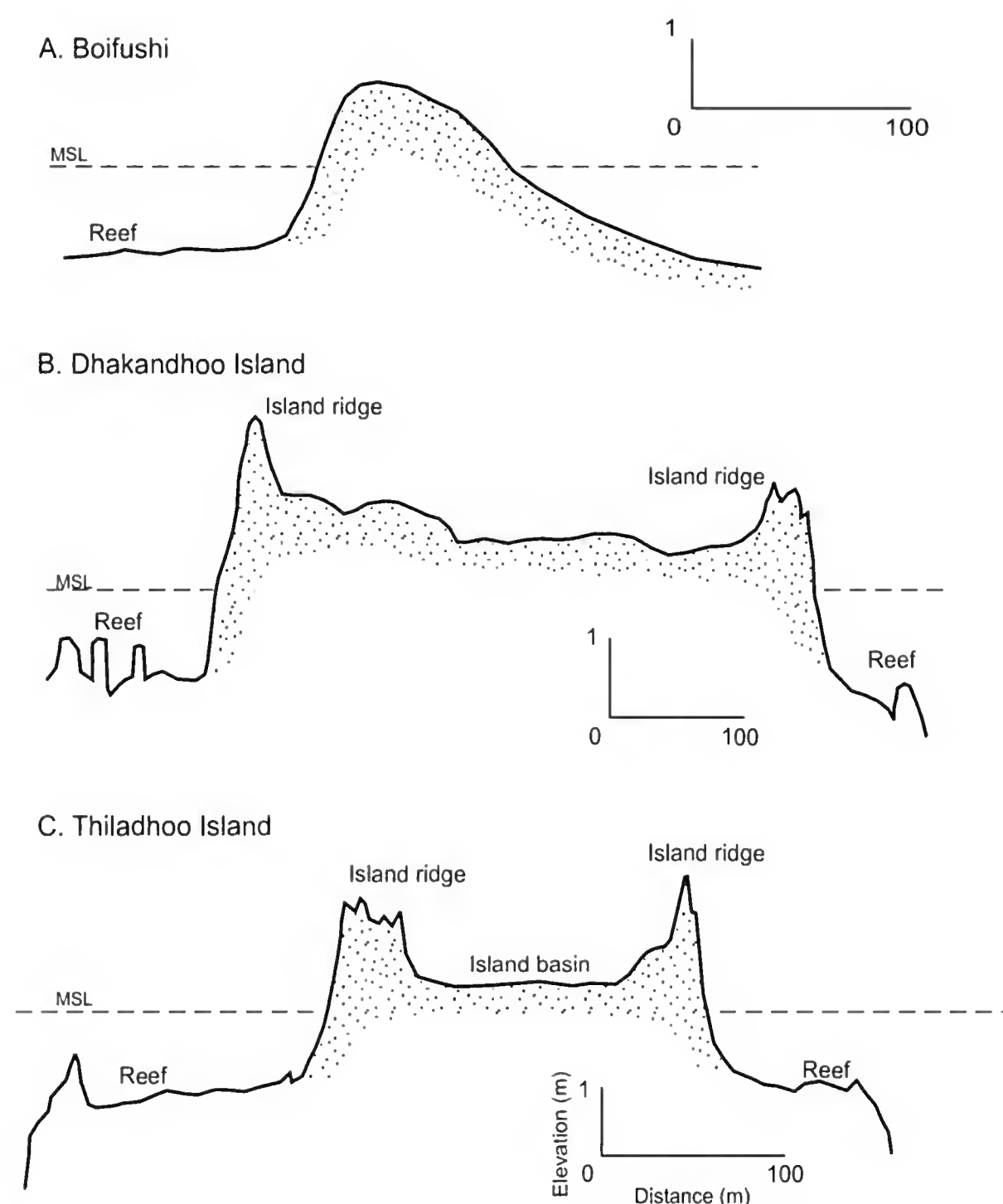


Table 3. Physical characteristics of islands in Baa atoll.

| Island name            | Length<br>(m) | Width<br>(m) | Area<br>(ha) | Ellipticity | Percent<br>occu. | Location<br>(P/I) |
|------------------------|---------------|--------------|--------------|-------------|------------------|-------------------|
| Nelivaru               | 55            | 20           | 0.1          | 0.36        | 0.1              | P                 |
| Ahivahfushi            | 67            | 40           | 0.1          | 0.60        | 0.1              | P                 |
| Kanufushee finolhu     | 80            | 25           | 0.1          | 0.31        | 0.1              | P                 |
| Kanufushee G. Finolhu  | 80            | 30           | 0.1          | 0.38        | 0.1              | P                 |
| Medhufinolhu           | 130           | 30           | 0.1          | 0.23        | 0.1              | P                 |
| Nibiligaa              | 123           | 15           | 0.5          | 0.12        | 1.0              | I                 |
| Ufuligili              | 250           | 30           | 0.5          | 0.12        | 0.2              | P                 |
| Kudadhoo               | 130           | 60           | 0.6          | 0.46        | 0.1              | P                 |
| Hanifaru               | 250           | 56           | 1.0          | 0.22        | 0.3              | P                 |
| Gemendhoo              | 150           | 100          | 1.2          | 0.67        | 34.6             | I                 |
| Boifushi <i>usc</i>    | 169           | 70           | 1.3          | 0.41        | 9.9              | P                 |
| Maddoo-hulhudhoo       | 180           | 130          | 1.6          | 0.72        | 37.7             | P                 |
| Keyodhoo               | 170           | 135          | 1.7          | 0.79        | 47.0             | I                 |
| Bathalaa               | 138           | 132          | 1.8          | 0.96        | 0.8              | P                 |
| Gaaviligili            | 330           | 150          | 1.9          | 0.45        | 2.1              | P                 |
| Aidhoo                 | 280           | 130          | 2.0          | 0.46        | 34.7             | P                 |
| Dhandhoo               | 230           | 130          | 2.0          | 0.57        | 19.8             | I                 |
| Hulhudhoo              | 224           | 200          | 2.2          | 0.89        | 44.3             | I                 |
| Dhigufaru vinagadu     | 250           | 67           | 2.4          | 0.27        | 0.3              | P                 |
| Bodufinolhu            | 750           | 60           | 2.5          | 0.08        | 0.1              | P                 |
| Thiladhoo              | 230           | 200          | 2.7          | 0.87        | 18.7             | I                 |
| Emboodhoo              | 300           | 100          | 2.8          | 0.33        | 21.8             | I                 |
| Milaidhoo              | 250           | 200          | 3.0          | 0.80        | 10.3             | I                 |
| Muthaafushi            | 630           | 75           | 3.0          | 0.12        | 4.3              | I                 |
| Veyofushi              | 300           | 180          | 3.2          | 0.60        | 2.4              | I                 |
| Voavah                 | 289           | 49           | 3.2          | 0.17        | 3.0              | I                 |
| Madhirivaadhoo         | 330           | 230          | 4.0          | 0.70        | 35.2             | P                 |
| Hirundhoo              | 400           | 150          | 4.1          | 0.38        | 38.4             | I                 |
| Kashidhoogiri          | 253           | 214          | 4.1          | 0.85        | 33.0             | P                 |
| Kashidupper <i>usc</i> | 358           | 25           | 4.3          | 0.07        | 0.8              | I                 |
| Miriyandhoo            | 430           | 180          | 4.8          | 0.42        | 16.6             | P                 |
| Dhakandhoo             | 400           | 230          | 4.8          | 0.58        | 46.7             | I                 |

| Island name      | Length<br>(m) | Width<br>(m) | Area<br>(ha) | Ellipticity | Percent<br>occu. | Location<br>(P/I) |
|------------------|---------------|--------------|--------------|-------------|------------------|-------------------|
| Kanufushi        | 530           | 180          | 7.2          | 0.34        | 2.6              | P                 |
| Funadhoo         | 430           | 350          | 7.8          | 0.81        | 44.7             | I                 |
| Kihaadhunfaru    | 600           | 230          | 8.2          | 0.38        | 12.7             | I                 |
| Udoodhoo         | 380           | 365          | 9.3          | 0.96        | 51.1             | I                 |
| Fares            | 630           | 220          | 10.2         | 0.35        | 3.5              | P                 |
| Mendhoo          | 530           | 280          | 10.5         | 0.53        | 25.8             | I                 |
| Dhunikolhu       | 600           | 250          | 11.3         | 0.42        | 0.5              | I                 |
| Vakkaru          | 750           | 250          | 11.8         | 0.33        | 4.8              | I                 |
| Horubadhoo       | 750           | 230          | 12.0         | 0.31        | 51.3             | I                 |
| Dhonfanu         | 680           | 220          | 12.6         | 0.32        | 26.4             | I                 |
| Kihavahhuruvalhi | 508           | 249          | 12.7         | 0.49        | 14.2             | I                 |
| Kendhoo          | 600           | 350          | 13.7         | 0.58        | 61.6             | I                 |
| Hibalhithoo      | 830           | 300          | 14.3         | 0.36        | 21.4             | P                 |
| Landaa-giraavaru | 950           | 250          | 14.5         | 0.26        | 4.6              | P                 |
| Mudhdhoo         | 675           | 350          | 16.0         | 0.52        | 47.4             | I                 |
| Kamadhoo         | 530           | 460          | 16.8         | 0.87        | 50.8             | P                 |
| Kudarikilu       | 521           | 391          | 16.8         | 0.75        | 38.1             | P                 |
| Maaddoo          | 1380          | 350          | 18.8         | 0.25        | 51.5             | P                 |
| Anhenunfushi     | 634           | 295          | 19.2         | 0.47        | 19.7             | P                 |
| Olhugiri         | 550           | 400          | 20.0         | 0.73        | 71.0             | P                 |
| Finolhos         | 900           | 300          | 20.5         | 0.33        | 46.0             | I                 |
| Eydafushi        | 770           | 415          | 22.2         | 0.54        | 38.5             | P                 |
| Maarikilu Kandu  | 708           | 426          | 22.2         | 0.60        | 42.2             | P                 |
| Maalhos          | 750           | 490          | 23.2         | 0.65        | 54.6             | P                 |
| Hithaadhoo       | 790           | 450          | 25.2         | 0.57        | 18.7             | P                 |
| Kihaadhoo        | 800           | 490          | 26.4         | 0.61        | 65.0             | I                 |
| Maamaduvvari     | 940           | 350          | 29.6         | 0.37        | 38.0             | P                 |
| Kunfunadhoo      | 1420          | 360          | 35.0         | 0.25        | 42.1             | P                 |
| Dharavandhoo     | 1320          | 480          | 45.5         | 0.36        | 48.9             | P                 |
| Thulhaadhoo      | 380           | 230          | 5.0          | 0.61        | 0.2              | P                 |
| Fonimagoodhoo    | 600           | 200          | 7.2          | 0.33        | 6.9              | P                 |

NB: Percent Occu. = percentage of reef platform occupied by island; P= peripheral reef, I=internal reef, usc = unvegetated sand cay



**Figure 7.** Characteristics morphologies of reef islands in Baa atoll. A) Convex morphology; B) Asymmetric ridge morphology; C) Basin morphology.

While island ridges are relatively high, the central island depression is substantially lower in elevation -typically less than 1.0 m above msl. While island morphologies can be reduced to three simple forms the surface morphology of islands exhibit complex morphologies at the island scale. For example, island surfaces can exhibit multiple ridge sequences. Furthermore, on some islands additional depressions exist that are occupied by mangrove (*faa*) or freshwater ponds (*kulhi*). At least three islands are known to have *kulhi* or *faa* (Dhakandhoo, Hirundhoo and Maamaduvvari). The presence of enclosed *kulhi* and *faa* signifies that small lagoons may have been closed through alongshore extension of island ridges during island development. Indeed, such a sequence of events has taken place on Maamaduvvari which was initially described by Gardiner (1903) as having a small lagoon but which has subsequently been occluded with the formation of a barrier across the northwestern section of the island.

### Unconsolidated Island Sediments

The reef islands of Baa Atoll are composed entirely of calcareous sediments derived from the skeletal remains of reefal organisms. However, the texture, composition of sediments and degree of lithification of island sediments do differ between islands.

*Gravel Deposits.* On wave exposed sectors of the atoll periphery, islands are composed of coarse coral rubble. For example, on Ahivahfushi (northwest), Gaaviligili (southwest) and Aidhoo (northeast) the ocean shoreline consists of a sequence of gravel ridges that represent phases of island accumulation (Fig. 8A, B). Gravel deposits have also been identified on Ufulgili, Olhugiri and Maamaduvvari. The gravels are composed almost entirely of coral clasts. However, the lagoon ends of islands appear to be composed of sand-size material forming spits that extend lagoonward across the reef platforms.

*Sand Deposits.* The majority of leeward peripheral islands and all lagoon islands are composed of sand-size calcareous sediments (Fig. 8C, D). An analysis of more than 107 beach samples from 10 islands in Baa Atoll indicated that sediment size ranged from 0.7 to 2.0 phi (0.6 mm to 0.25 mm) although the mean size was approximately 1.4 phi (0.38 mm, Cameron, 2002). Ali (2000) reported a similar size range for island sediments of Baa Atoll. Sand islands consist of a vegetated island core, which is surrounded by an unvegetated and mobile beach.

The composition of 13 island sediment samples, from 9 islands, was examined by Ali (2000) (Table 4). Results indicate that sediment composition is dominated by coral (20-66%). *Halimeda* (up to 47%) and molluscan fragments are of secondary importance in deposits with foraminifera and other components comprising subordinate fractions (<10%). However, the number of samples analysed were too few to provide a robust assessment of the sediment composition or spatial differences in constituents contributing to islands. Such differences can occur within islands and are discussed later.

Table 4. Summary of the skeletal composition of 13 island samples from Baa Atoll.

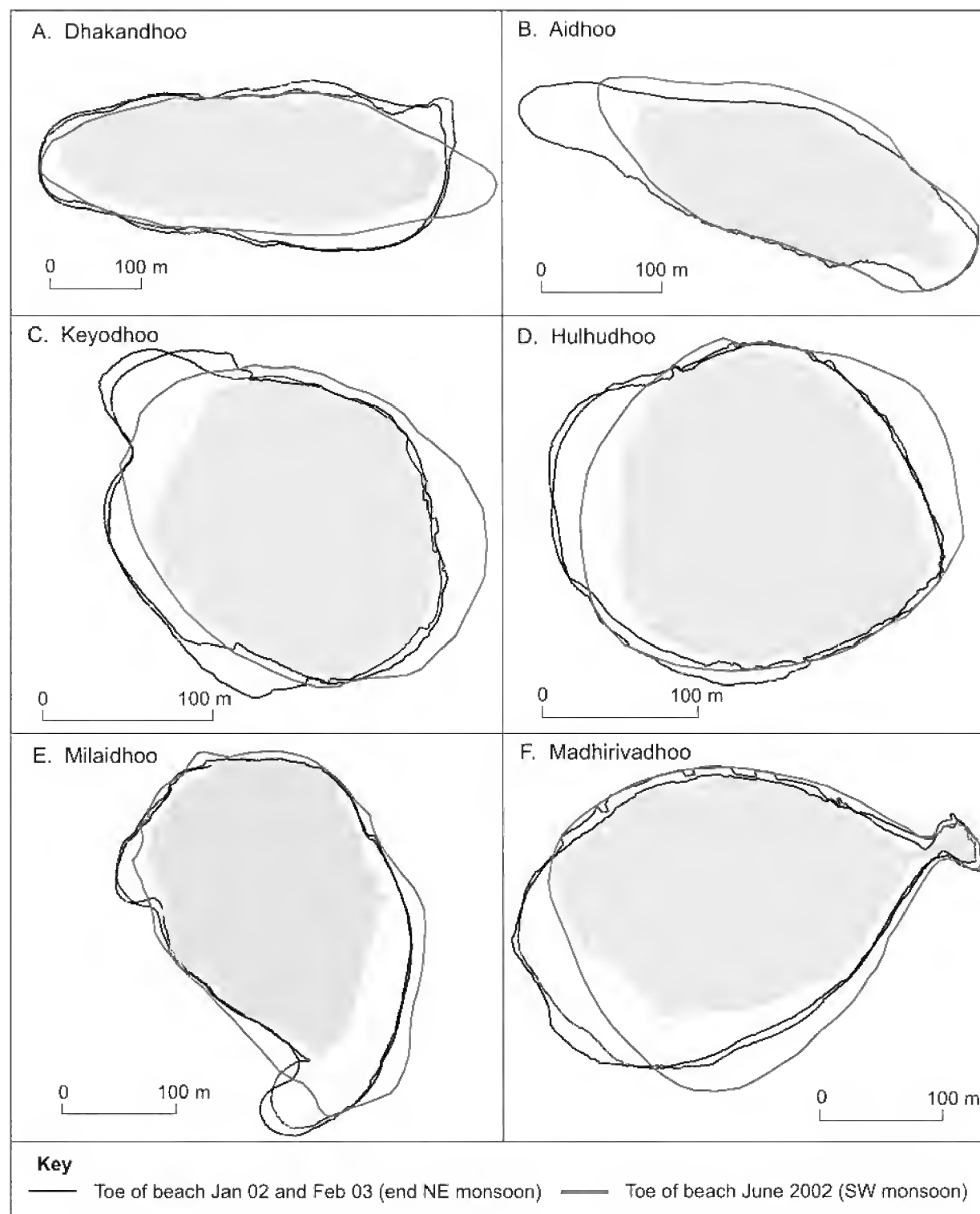
| Island      | Depth (m) | Coral | Mollusc | Halim. | Foram | Alcyon. | Crust/Echin | Coralline algae | Unkn |
|-------------|-----------|-------|---------|--------|-------|---------|-------------|-----------------|------|
| Aidhoo      | 0.75      | 62.7  | 18.1    | 2.2    | 5.0   | 5.3     | 3.3         | 0.0             | 3.3  |
| Aidhoo      | 1.20      | 40.7  | 25.0    | 11.6   | 7.5   | 6.4     | 5.4         | 0.0             | 3.4  |
| Bodufinolhu | 1.25      | 38.1  | 17.9    | 26.8   | 6.5   | 4.6     | 3.3         | 0.7             | 2.2  |
| Fares       | 2.0       | 48.4  | 13.4    | 20.6   | 8.4   | 2.3     | 3.1         | 0.2             | 3.7  |
| Hanifaru    | 0.98      | 52.2  | 7.9     | 21.7   | 7.6   | 1.8     | 5.3         | 0.7             | 2.8  |
| M-Hulhudhoo | 0.8       | 59.6  | 12.6    | 0.0    | 16.5  | 4.0     | 1.3         | 0.0             | 6.0  |
| M-Hulhudhoo | Beach     | 53.6  | 23.6    | 1.4    | 5.2   | 7.2     | 3.5         | 0.6             | 4.9  |
| Mendhoo     | 1.6       | 48.2  | 15.9    | 6.9    | 7.2   | 10.5    | 7.2         | 1.1             | 3.0  |
| Nelivaru    | 2.95      | 44.7  | 17.5    | 17.3   | 11.9  | 0.8     | 3.6         | 0.4             | 3.8  |
| Olhugiri    | 1.20      | 66.1  | 13.6    | 0.0    | 6.1   | 6.1     | 5.2         | 0.0             | 2.9  |
| Olhugiri    | 1.8       | 42.8  | 23.6    | 18.3   | 9.5   | 1.3     | 2.2         | 0.7             | 1.6  |
| Udoodhoo    | 1.15      | 20.6  | 8.3     | 47.4   | 9.3   | 7.5     | 3.0         | 0.0             | 4.0  |
| Udoodhoo    | Beach     | 55.8  | 12.5    | 1.3    | 10.3  | 8.8     | 4.7         | 3.5             | 3.1  |

Depth = depth below island surface; Halim. = *Halimeda*; Foram. = foraminifera; Alcyon. = Alcyonarian spicules; Crust/Echin. = Crustacean and Echinoids; Unkn. = unknown. Source (Ali, 2000).



**Figure 8.** Examples of unconsolidated sedimentary materials comprising islands in Baa atoll. Gravel ridges on Gaaviligili (A) and Aidhoo (B); sand spit on Aidhoo (C) and typical beach on Milaidhoo (D) Location of islands shown in Figure 2.

*Mobile Beaches.* Beaches composed of sand-size material are very dynamic, with shorelines shifting position markedly at seasonal timescales. Seasonal monitoring of beach position using Global Positioning System (GPS) surveys was instigated on 13 islands in Baa Atoll in 2002 and provides a useful baseline to assess ongoing geomorphic changes in islands (Kench and Brander, 2006). Figure 9 shows summary GPS surveys documenting the position of beaches on selected islands between monsoon seasons. The data show large changes in beach position between monsoon periods. However, the net change in beach position was minimal on an annual basis (Kench and Brander, 2006). Furthermore, the degree of shoreline change appears to vary between islands of differing shape. For example, circular islands (e.g. Hulhudhoo) display larger changes in beach position around the island shoreline, whereas the elongate islands display more constrained shoreline change, principally around the apexes of islands. Based on detailed hydrodynamic investigations it has been established that observed beach change is driven by monsoonally-forced oscillations in wave and current processes (Kench et al., 2009b, c).



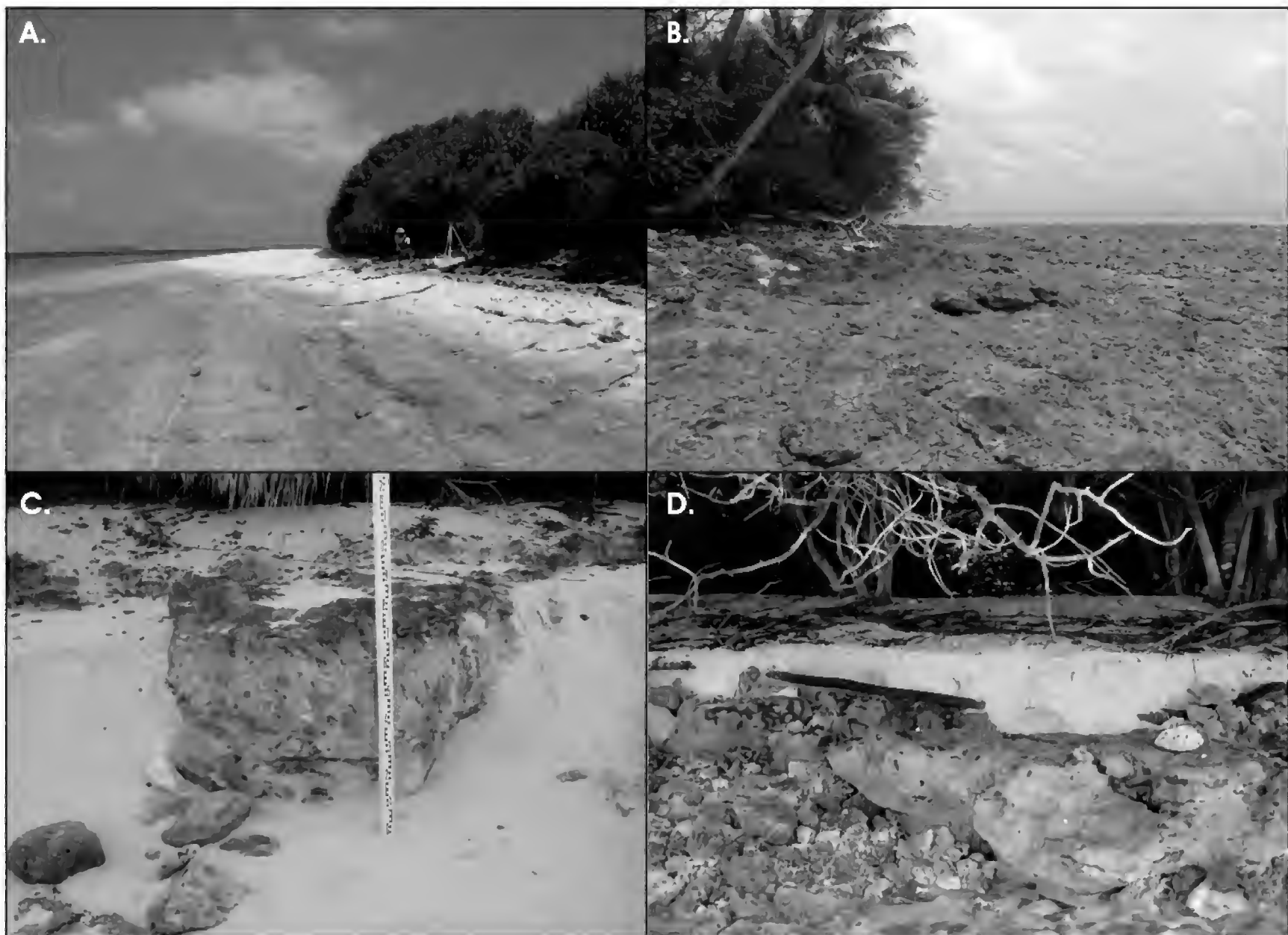
**Figure 9.** Seasonal beach change around selected islands in Baa Atoll. Selected islands are part of a monitoring network in the atoll. Location of islands shown in Figure 2.

Seasonal beach change is geomorphically important. It is responsible for large volumetric fluxes of sediment around island shorelines on a seasonal basis; it regulates the transfer of sediments between the reef and vegetated core of the island surface (Kench 2008), and it occupies the inner reef flat surface and prevents coral growth. Indeed the footprint of beach demarcates the boundary of the inner reef platform moat. Beyond the moat upward reef growth has continued until confined by sea level, with the living reef edge elevated up to 1.0 m above the moat surface.

### Lithified Island Sediments

A range of lithified sediments are found on the islands of Baa Atoll (Fig. 10). They are found in distinct geomorphic zones, have different modes of formation and occupy different elevations with respect to sea level. The lithified sediments can in some cases be extensive and can assist in the stabilisation of islands and their shorelines.





**Figure 10.** Examples of consolidated sediments on islands of Baa Atoll. A) Continuous beachrock surrounding the Keyodhoo Island shoreline. B) Conglomerate rock that outcrops on island shorelines. C) Cay sandstone outcropping on island shoreline and typical of massive rock located beneath the island surface in some islands. D) Phosphate rock outcropping on the Keyodhoo shoreline. Note brown colouration of rock. Phosphate rock is found beneath the island surface on a number of islands in Baa Atoll.

*Beachrock* is prevalent on many islands in the atoll. (Fig. 10A). Distinctive in its intertidal elevation and in the slope that mirrors the contemporary beach, on some islands beachrock forms near continuous deposits that encircle islands (e.g. Keyodhoo, Hulhudhoo, and Udoodhoo). In these islands beachrock is seasonally buried by the movement of the contemporary beach. Beachrock is also found detached from island shorelines where it documents previous island positions on the reef platform.

*Conglomerate.* Lithified deposits of gravel and sand occur on the high energy shores of a number of peripheral islands (Fig. 10B). Such deposits do not possess the sloping surface characteristic of beachrock and are interpreted as cemented high energy deposits or even cemented gravel ridges that have subsequently been eroded. Examples can be found on Aidhoo and Gaaviligili. Gardiner (1903) also described this deposit on Maamaduvvari although at the time he interpreted this rock as evidence for higher sea level.

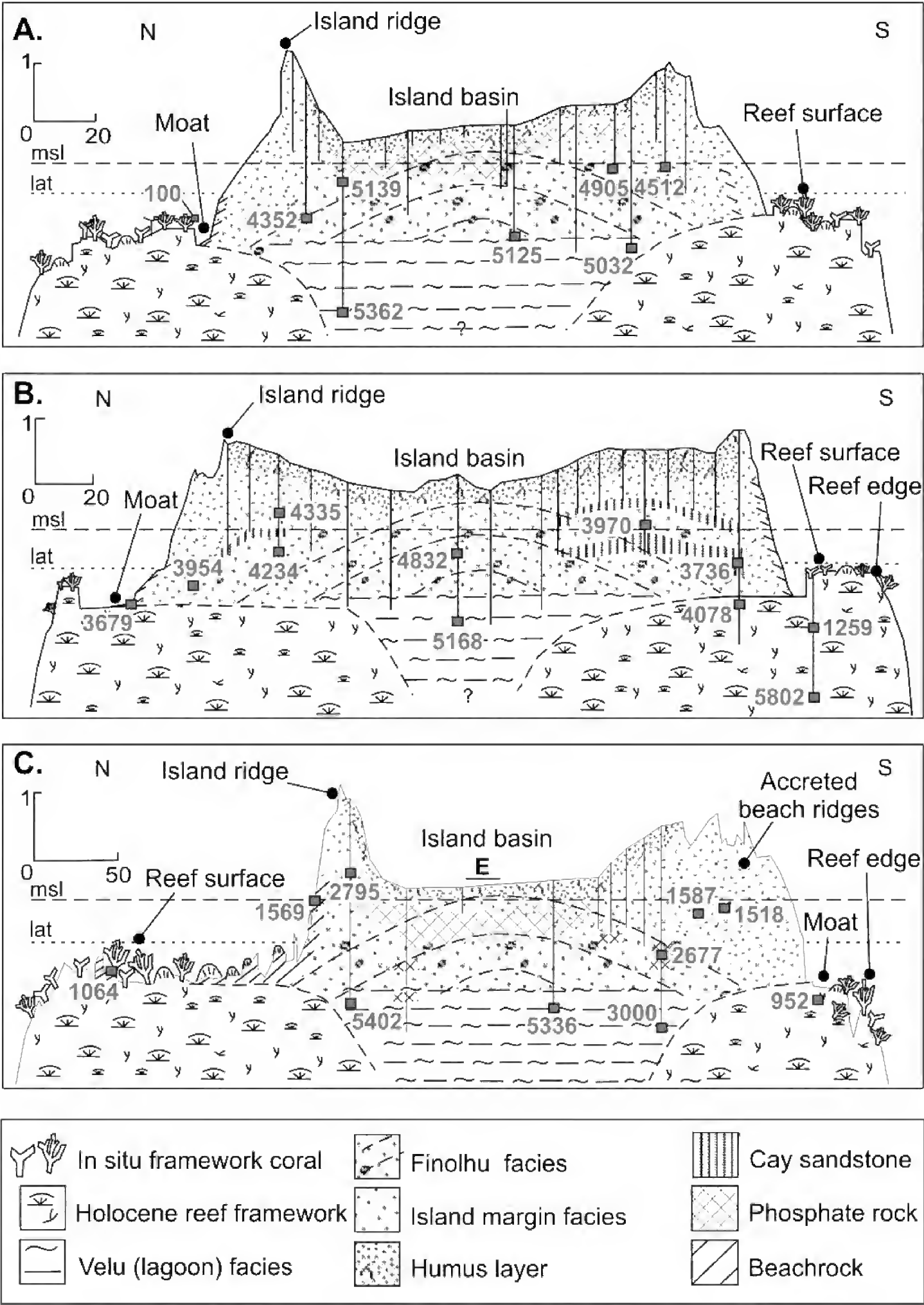
*Cay sandstone* can form at the level of the water table beneath islands. Cay sandstone consists of cemented bioclastic sand-size sediments and is distinguished from beachrock by near horizontal bedding. In Baa Atoll cay sandstone is not found on all islands but where it is present can be more than 1 m thick (Fig. 10C).



*Phosphate rock* can occur and forms at the water table and within the soil horizons of islands in Baa Atoll. Phosphate rock also comprises cemented reefal bioclastic sediments; however, the grains are replaced by phosphate minerals (Hopley, 2011). Phosphate rocks in Baa Atoll are distinguished by their light orange to brown colouration (Fig. 10D). Island cores extracted from a range of islands indicate that phosphate rock is not ubiquitous. However, where phosphate rock occurs it can form continuous cemented layers that underlie the island surface. For example, on Dhakandhoo and Thiladhoo islands on the west and eastern sides of the atoll phosphate rock is found as a continuous layer beneath the island. On Keyodhoo and some other islands, erosion of the shoreline has exposed phosphate rocks which outcrop at the shoreline. Investigations from Dhakandhoo show that the phosphate layer has been mined by local communities for the purposes of agricultural fertilisation.

### Island Evolution

The detailed evolution of reef islands in Baa Atoll has been investigated by Kench et al. (2005) based on detailed coring and radiometric dating of island sediments. A summary of the radiometric dates and chronostratigraphy of three islands is presented in Figure 11 and Table 5. The data show that island sediments are of mid-Holocene age. Chronostratigraphic analysis of the dated sediments relative to the underlying reef provides insights into the temporal development of the islands in Baa Atoll. A three-phase model of island formation has been proposed (Kench et al., 2005). First, the small reef platform islands appear to have been deposited over infilled faro lagoons (velu). As reef growth approached sea level they encountered wave base, which provided a process mechanism to flush reefal sediments into lagoons. Radiometric ages of suggest velu sediments were deposited approximately 5,500 to 5,000 yBP. Second, island accumulation across velu deposits was initiated approximately 5,000 yBP. The narrow range of ages of island sediments ( $5,125 \pm 61$  to  $3,736 \pm 57$  yBP), particularly on Dhakandhoo and Hulhudhoo indicate that islands accumulated rapidly with deposition of the vegetated core of islands effectively complete by 4,000 yBP. The third phase spans the past 4,000 years and is characterised by cessation of island building. Lithification of sediments as cay sandstones, phosphate rocks and beachrock has assisted in the stabilisation of islands. Further dates on reefal materials (Tables 1 and 5) show that continued vertical reef growth occurred over the past 4,000 years which would have progressively closed down the process window from that under which islands were constructed. The interaction between vertical reef growth on the outer reef and seasonal oscillations in beach position, which constrained vertical reef development on the inner reef, is responsible for development of nearshore moat that surrounds reef islands.



**Figure 11.** Morphostratigraphy of reef and island cross sections, Baa Atoll. Location of islands shown on Figure 2. A) Dhakandhoo B) Hulhudhoo C) Thiladhoo. Conventional radiocarbon ages shown in red are in correct stratigraphic position (see Table 5 for error terms).

Table 5. Radiocarbon dates from detailed morphostratigraphic studies of three islands in Baa Atoll, Maldives.

| Island     | Laboratory code | Facies designation and material | Depth relative to MSL(m) | Conventional age (yr B.P.) | Calibrated age range (95.4% probability)<br>(cal. yr B.P.) |
|------------|-----------------|---------------------------------|--------------------------|----------------------------|--|
| Dhakandhoo | Wk 11293        | Velu facies: sand               | −0.29                    | 5139 ± 62                  | 5550–5200  |
|            | Wk 11294        | Velu facies: sand               | −2.55                    | 5362 ± 63                  | 5730–5440  |
|            | Wk 11295        | Velu facies: sand               | −1.58                    | 5032 ± 60                  | 5410–5000  |
|            | Wk 11296        | Finolhu facies: sand            | −1.23                    | 5125 ± 61                  | 5530–5130  |
|            | Wk 11297        | Finolhu facies: sand            | 0.05                     | 4905 ± 51                  | 5230–4860  |
|            | Wk 12661        | Finolhu facies: sand            | −0.05                    | 4512 ± 42                  | 4680–4440  |
|            | Wk 12662        | Finolhu facies: sand            | −1.18                    | 4352 ± 44                  | 4880–4250  |
| Hulhudhoo  | Wk 12660        | Dead <i>in situ</i> coral       | −0.92                    | 105 ± 0.5                  | Modern   |
|            | Wk 12097        | Finolhu facies: sand            | 0.26                     | 4335 ± 46                  | 4460–4210  |
|            | Wk 11298        | Finolhu facies: sand            | −0.29                    | 4234 ± 52                  | 4320–3970  |
|            | Wk 11299        | Finolhu facies: sand            | −0.34                    | 4832 ± 59                  | 5140–4790  |
|            | Wk 11300        | Velu facies: sand               | −1.29                    | 5168 ± 62                  | 5560–5260  |
|            | Wk 11301        | Finolhu facies: sand            | −0.51                    | 3736 ± 57                  | 3640–3350  |
|            | Wk 11302        | In situ reef rock               | −1.17                    | 4078 ± 70                  | 4140–3720  |
|            | Wk 11303        | Reefal sand                     | −1.80                    | 1259 ± 47                  | 780–570  |
|            | Wk 11304        | In situ coral                   | −2.50                    | 5802 ± 60                  | 6210–5910  |
|            | Wk 12663        | In situ fossil <i>Porites</i>   | −0.26                    | 3679 ± 40                  | 3550–3340  |
|            | Wk 12664        | Finolhu facies: sand            | −0.145                   | 3970 ± 40                  | 3950–3720  |
| Thiladhoo  | Wk 12665        | Island-margin sand              | −1.13                    | 3954 ± 40                  | 3930–3700  |
|            | Wk 11305        | Finolhu facies: sand            | −0.79                    | 2677 ± 57                  | 2340–2050  |
|            | Wk 11306        | Velu facies: sand               | −1.84                    | 3000 ± 55                  | 2750–2430  |
|            | Wk 11307        | Island-margin sand              | 0.40                     | 2795 ± 54                  | 2540–2160  |
|            | Wk 11308        | Velu facies: sand               | −1.52                    | 5402 ± 54                  | 5750–5480  |
|            | Wk 11309        | Beachrock                       | 0.18                     | 1064 ± 45                  | 630–460  |
|            | Wk 11310        | Beachrock                       | 0.00                     | 1569 ± 44                  | 1100–890   |
|            | Wk 11311        | In situ fossil <i>Porites</i>   | −1.09                    | 952 ± 46                   | 530–330  |
|            | Wk 12666        | Velu facies: sand               | −1.52                    | 5336 ± 43                  | 5680–5460  |
|            | Wk 12667        | Island-margin sand              | −0.14                    | 1518 ± 37                  | 1030–840   |
|            | Wk 12668        | Island-margin: sand             | −0.39                    | 1587 ± 36                  | 1100–920   |

*Note:* Radiocarbon dates obtained from the Radiocarbon Dating Laboratory, University of Waikato, New Zealand. Ages calibrated by using OxCal version 3.5 (Bronk Ramsey, 2001) with the marine data set (Stuiver et al., 1998) and Delta-R value of  $132 \pm 25$  as best estimate for the central Indian Ocean reservoir effect (Southon et al., 2002). From Kench et al., (2005).

It is evident that a major phase of island formation occurred in Baa Atoll between 5,000 and 4,000 yBP. Additional near surface radiocarbon dates from a number of other islands are consistent with this interpretation (Table 6). Comparison of the chronology of island formation with the established sea level curve in Baa Atoll provides further insights into the relationship between sea level, island formation and island persistence in the Holocene. First, evidence from the reef growth record (Fig. 6) suggests islands formed at sea level over slightly submergent reef platforms. This implies that the water depth and process window for island accumulation across reef surfaces was higher during the period of island formation. Second, emergent microatolls indicate that sea level rose to 0.5 m above present 2,000-4,000 years ago. This post-dates island formation and indicates islands in Baa Atoll have been subject to higher sea levels in the mid- to late Holocene. During this period continued vertical reef growth occurred. The combination of vertical growth of the outer reef and late Holocene fall in sea level has reduced the magnitude of the process window that can access and force morphological change of reef islands.

Table 6. Sundry near surface dates from a range of reef islands in Baa Atoll, Maldives.

| Island        | Laboratory<br>code | Facies designation and<br>material | Depth relative<br>to MSL(m) | Conventional<br>age (yr B.P.) |
|---------------|--------------------|------------------------------------|-----------------------------|-------------------------------|
| Mendhoo       | WK 7078            | Beach sand                         | -                           | 1370 ± 50                     |
|               | Wk 6175            | West island surface                | -0.35                       | 2300 ± 60                     |
|               | Wk 5839            | Central island                     | -0.78                       | 3520 ± 60                     |
| Udoodhoo      | Wk 6337            | Beach sand                         | -                           | 1390 ± 50                     |
|               | Wk 5829            | Central east                       | -0.8                        | 4500 ± 60                     |
|               | Wk 6170            | Central west                       | -0.64                       | 4710 ± 70                     |
|               | Wk 6331            | Central east                       | -0.54                       | 4960 ± 60                     |
| Hanifaru      | Wk 6338            | Centre of island                   | 0.21                        | 1500 ± 50                     |
| Nelivaru      | Wk 6173            | Centre                             | 2.3*                        | 1560 ± 50                     |
|               | Wk 6336            | Beach                              | -                           | 1570 ± 50                     |
|               | Wk 6174            | Centre                             | 2.9*                        | 2040 ± 50                     |
| Bodufinholhu  | Wk 6168            | Centre of island                   | 0.17                        | 1590 ± 50                     |
| Hithaadhoo    | Wk 6166            | Centre and northern                | 2.01*                       | 1610 ± 60                     |
| Hibalhiddoo   | Wk 5834            | West side island                   | -0.48                       | 1630 ± 50                     |
|               | Wk 5833            | East side island                   | -0.37                       | 1850 ± 50                     |
| Muthaafushi   | Wk 6172            | East side island                   | -0.33                       | 1770 ± 50                     |
| Fonimagoodhoo | Wk 7079            | North                              | 1.14*                       | 1910 ± 60                     |
|               | Wk 7082            | South,                             | 0.75*                       | 2260 ± 60                     |
| Nibiligaa     | Wk 6335            | Central island                     | -0.31                       | 1980 ± 50                     |
|               | Wk 5830            | Central island                     | -0.64                       | 2240 ± 50                     |
| Fares         | Wk 6171            | Eastern island                     | -0.45                       | 1980 ± 60                     |
|               | Wk 5840            | Central east                       | -0.55                       | 3200 ± 60                     |
| Maamaduvvari  | Wk 6167            | West island                        | -0.54                       | 1630 ± 50                     |

|                   |         |                         |       |           |
|-------------------|---------|-------------------------|-------|-----------|
|                   | Wk 7080 | South island surface    | -0.05 | 2160 ± 60 |
|                   | Wk 5836 | Southeast               | -0.24 | 2270 ± 60 |
| Olhugiri          | Wk 6333 | South side island       | 0.43  | 2010 ± 60 |
|                   | Wk 5832 | South side island       | -0.72 | 2040 ± 60 |
|                   | Wk 5831 | Centre                  | 0.50  | 2870 ± 60 |
| Maaddoo-hulhudhoo | Wk 6329 | Beach                   | -     | 2060 ± 50 |
|                   | Wk 6332 | Coral in phosphate rock | -     | 4220 ± 80 |
|                   | Wk 6165 |                         | 0.12  | 4850 ± 80 |
| Maaddoo           | Wk 6330 | Western island          | -0.33 | 2250 ± 60 |
|                   | Wk 6334 | Northeast               | -0.2  | 2280 ± 60 |
|                   | WK 5837 | Northeast island        | 0.52  | 2870 ± 60 |
| Dhoogadu finolhu  | Wk 7081 | Cay sandstone           | -     | 2190 ± 60 |
| Gemendhoo         | Wk 5838 | Central island          | -0.2  | 2880 ± 60 |
| Aidhoo            | Wk 6339 | Central island          | 0.44  | 2920 ± 50 |
|                   | Wk 5835 | Central island          | -0.06 | 3130 ± 60 |
| Kamadhoo          | Wk 6169 | Southeast island        | 1.88* | 3910 ± 60 |

*Note:* Radiocarbon dates obtained from the Radiocarbon Dating Laboratory, University of Waikato, New Zealand. From Ali, 2000.

## CONCLUSIONS

Historically there have been few investigations of the geomorphology of the reefs and islands of Baa Atoll. However, over the past decade investigations of islands in Baa Atoll have significantly increased understanding of the geomorphology, morphodynamics and evolution of reefs and islands.

Studies show a significant variation in the morphology and sedimentary character of islands. There is also a distinct spatial distribution of islands with most peripheral islands found on the east to southeastern atoll rim. Lagoon islands also tend to be located in the central and eastern side of the atoll.

This pattern of island distribution can be explained by net wave energy inputs to the atoll. Calculations of a gross wave energy balance across the atoll (Kench et al., 2006) identify a distinct west to east energy gradient which has implications for reef island presence, shape and location on reef platforms and provides quantitative support for Gardiner's (1903) and Sewell's (1936b) hypothesis that exposure to wave energy can account for the presence of islands. Island formation is constrained on the exposed western reef rim as a result of continual high magnitude wave energy inputs that sweep sediments across and off the reef platforms. Consequently, the few islands that do occur on the western atoll rim are either found on the leeward locations of broad reef flats or are composed of gravel. The more sheltered, lower energy lagoonal reef platforms combined with the circular shape of these reef platforms has two effects: i) it ensures reef top sediments are trapped on reef surfaces through oscillating monsoonal conditions, thus contributing to island building, and ii) these islands occupy a large proportion of the available reef surface. In contrast, the eastern atoll rim is dominated by a net easterly

energy balance (of lower magnitude than the western atoll rim) and the most exposed islands are located on the western sides of reef platforms.

Variations in the sedimentary character of islands are a function of the grade of sediment available for island building and hydrodynamic energy. Consequently, islands in exposed high-energy settings, close to the reef edge of the atoll rim are typically composed of gravel or rubble size material. In contrast, lagoonal and leeward reef islands are composed of sand-size sediments.

Baa Atoll is the location of the first systematic monitoring programme established to examine the morphological adjustment of atoll islands. Seasonal monitoring of the island shorelines has shown that islands are morphologically dynamic and are able to adjust their position around the vegetated core of islands in response to variations in incident wave processes (Kench and Brander, 2006). Monitoring has also established the impact of extreme events on the morphological adjustment of islands (Kench et al., 2006, 2007, 2008).

Studies of the Holocene evolution of the reefs and islands show the reefs underwent a rapid phase of development between 8,000 and 6,000 yBP. Islands are of mid-Holocene age and formed in a narrow window 5,000-4,000 yBP across infilled lagoons. Since formation the vegetated island cores have remained relatively stable allowing formation of cay sandstone and phosphate rocks.

Collective studies of the islands of Baa Atoll have important implications for the future of coral reef islands. In particular, confirmation of a sea level highstand 2,000-3,500 yBP allows critical re-evaluation of the relationship between sea level, reef growth and island formation. In the Maldives islands formed 5,000 – 4,000 years ago (Kench et al., 2005) and persisted as sea level rose to  $0.5 \pm 0.1$  m above present during the highstand ca 2,000-4,000 cal yBP. Consequently, Maldivian islands provide a geological analogue that demonstrates reef islands are capable of accommodating rising sea level comparable to that projected for the next century.

While studies of the reef islands of Baa Atoll have provided significant new insights into reef island formation and change, which have global application, extrapolation of the results to other atolls in the Maldives should be undertaken with caution. Baa Atoll is an open atoll with numerous patch reefs. Islands typically occupy the surface of these patch reefs. Consequently observations are likely to extend to similar structured atolls. However, the Maldives archipelago is comprised of 26 atolls many of which have differing reef structure and which straddle 850 km of latitude. Consequently, the reefs and islands are likely to reflect latitudinal variations in morphology and morphodynamics. More extensive studies of islands throughout the archipelago are required to develop a comprehensive understanding of the diversity of reef and island types.



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